Single Top Production as a Window to Physics Beyond the Standard Model

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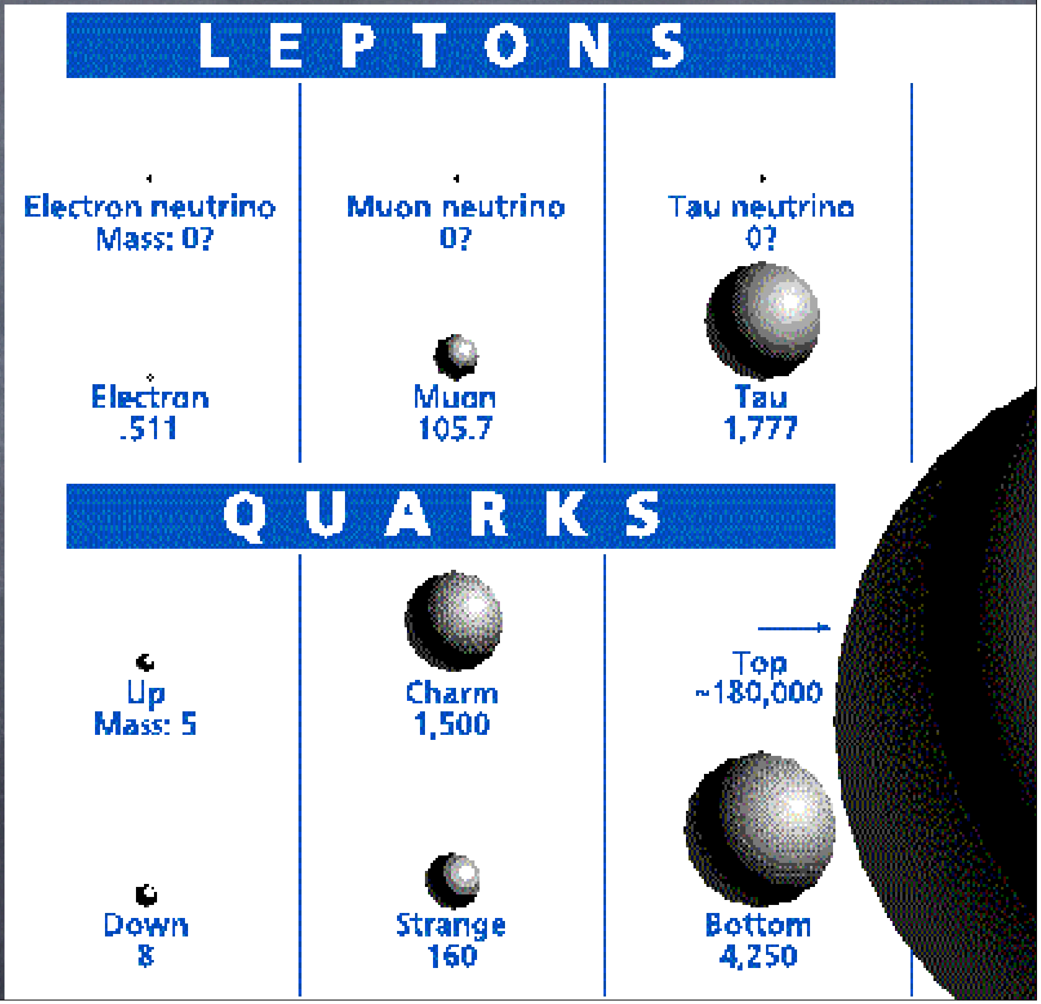
Outline

- Why study single top production?
- Single top in the Standard Model
- Beyond the SM
- Outlook

Why study single top?

- In the SM, top is superficially much like other fermions.
- What really distinguishes it is the huge mass, roughly 40x larger than the next lighter quark, bottom.
- This may be a strong clue that top is special in some way.
- It also implies a special role for top within the Standard model.
- Top is only fermion for which the coupling to the Higgs is important: it is a laboratory in which we can study EWSB.
- Single top, as a measure of top's weak interactions, is the **perfect** place to start.

SM Fermions



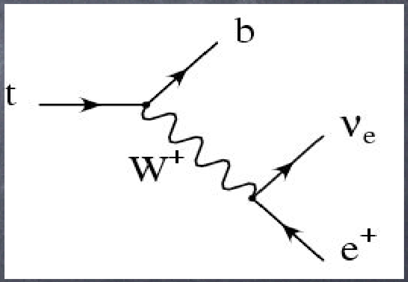
Top's EW Interactions

- Single top is our primary means to measure top's CC interactions.
- If top indeed plays a special role in EWSB, we would expect its weak interactions would be the place in which we could realize that it is special. Thus, there is interest beyond t t production.
- We know that top has a weak interaction, but not much beyond that.
- This information comes from the decay, t -> W b.

W*$^{\mu}$-*t*-*b vertex:

$$\frac{gV_{tb}}{2}\gamma^{\mu}(1-\gamma_5) \Rightarrow \Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}}|V_{tb}|^2 + \ldots$$

Left-handed!



- However, because Γ_t is much smaller than experimental resolutions, it is very difficult to use the decay to measure the magnitude of the weak interaction.

V_{tb}, V_{ts}, V_{td}

- We actually already know something about V_{tb} in the SM from the Unitarity of the CKM matrix.

- So amazingly enough in the SM we know V_{tb} to about 4 decimal places!

- But physics beyond the SM can easily modify this assumption... for example a fourth generation of quarks which mix with the third generation!

3 generation CKM matrix

$$\begin{bmatrix} 0.9739-0.9751 & 0.221-0.227 & 0.0029-0.0045 \\ 0.221-0.227 & 0.9730-0.9744 & 0.039-0.044 \\ 0.0048-0.014 & 0.037-0.043 & 0.9990-0.9992 \end{bmatrix}$$

$$VV^\dagger = 1 \quad \Rightarrow \quad |V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1$$

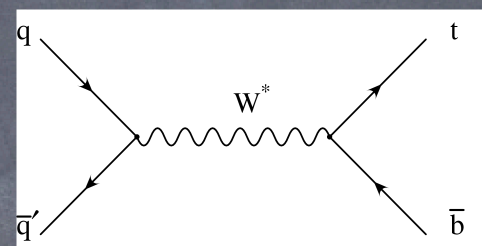
4+ generation CKM matrix

$$\begin{bmatrix} 0.9730-0.9746 & 0.2174-0.2241 & 0.003-0.0044 & \ldots \\ 0.213-0.226 & 0.968-0.975 & 0.039-0.044 & \ldots \\ <0.08 & <0.11 & 0.07-0.9993 & \ldots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

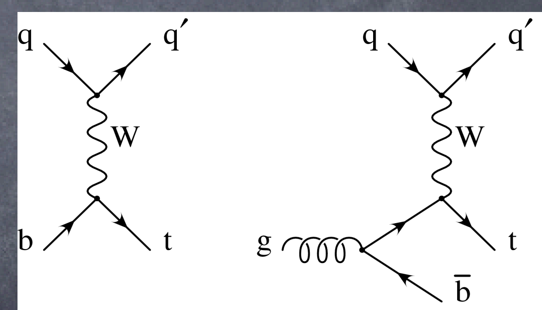
PDG: http://pdg.lbl.gov/pdg.html

Single Top in the SM

- Single top at hadron colliders is dominantly through reactions involving a W boson and a bottom quark.
- Three sub-processes:
  - s-channel: time-like W boson

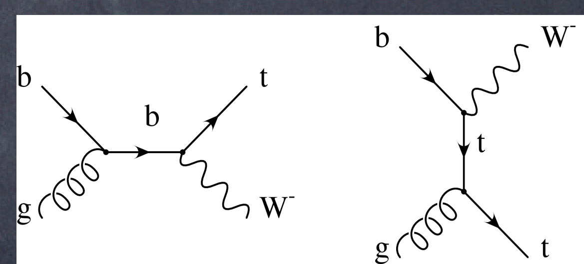


  - t-channel: space-like W boson (also known as "W-gluon fusion")

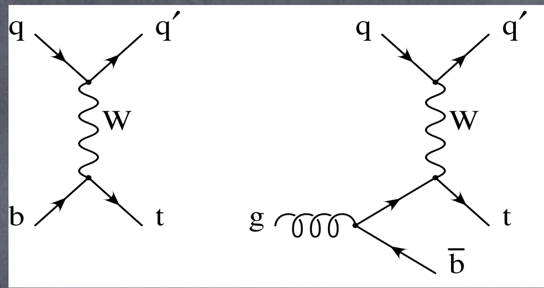


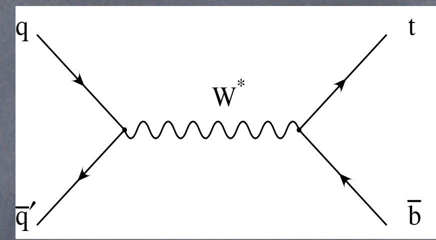
  - tW production: real W boson

(Too small to see at the Tevatron; important at LHC)



Signals at the Tevatron



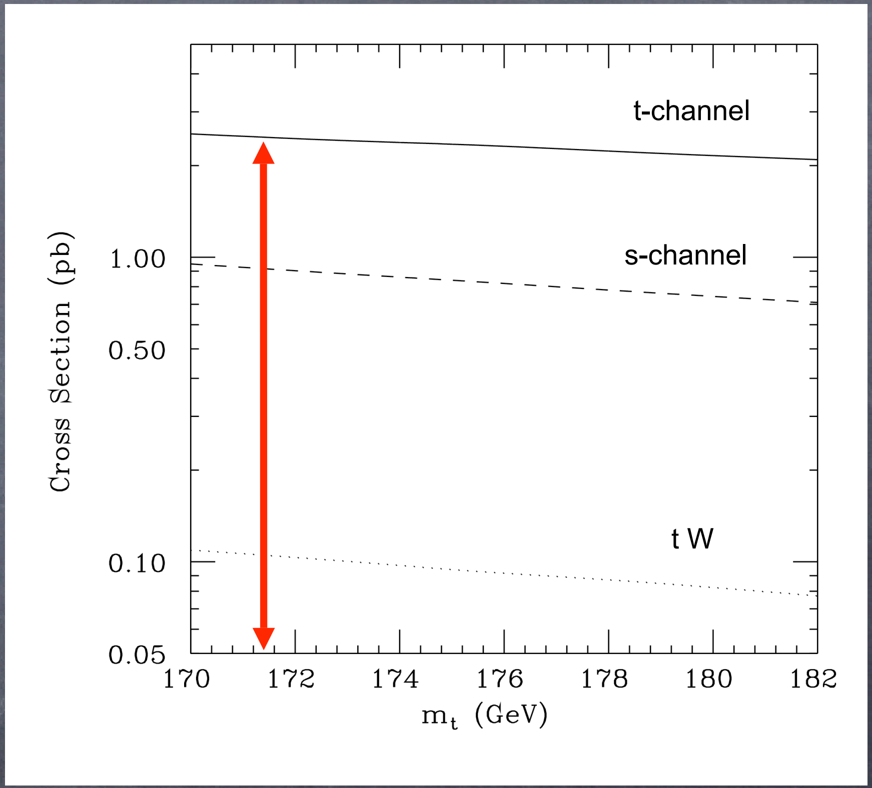


- The t-channel mode has the usual top decay signature, W b plus the extra unflavored jet.
  - The W is usually assumed to decay into a charged lepton and missing Energy (BR ~ 2/9 for e's and μ's).
  - The extra jet is usually fairly forward (y ~ 2) and with a pT ~ mW / 2.
- The s-channel mode also has t -> W b plus the extra bottom-initiated jet.
  - The tagging of that extra b is very useful to separate the s-channel from backgrounds.

Cross Sections

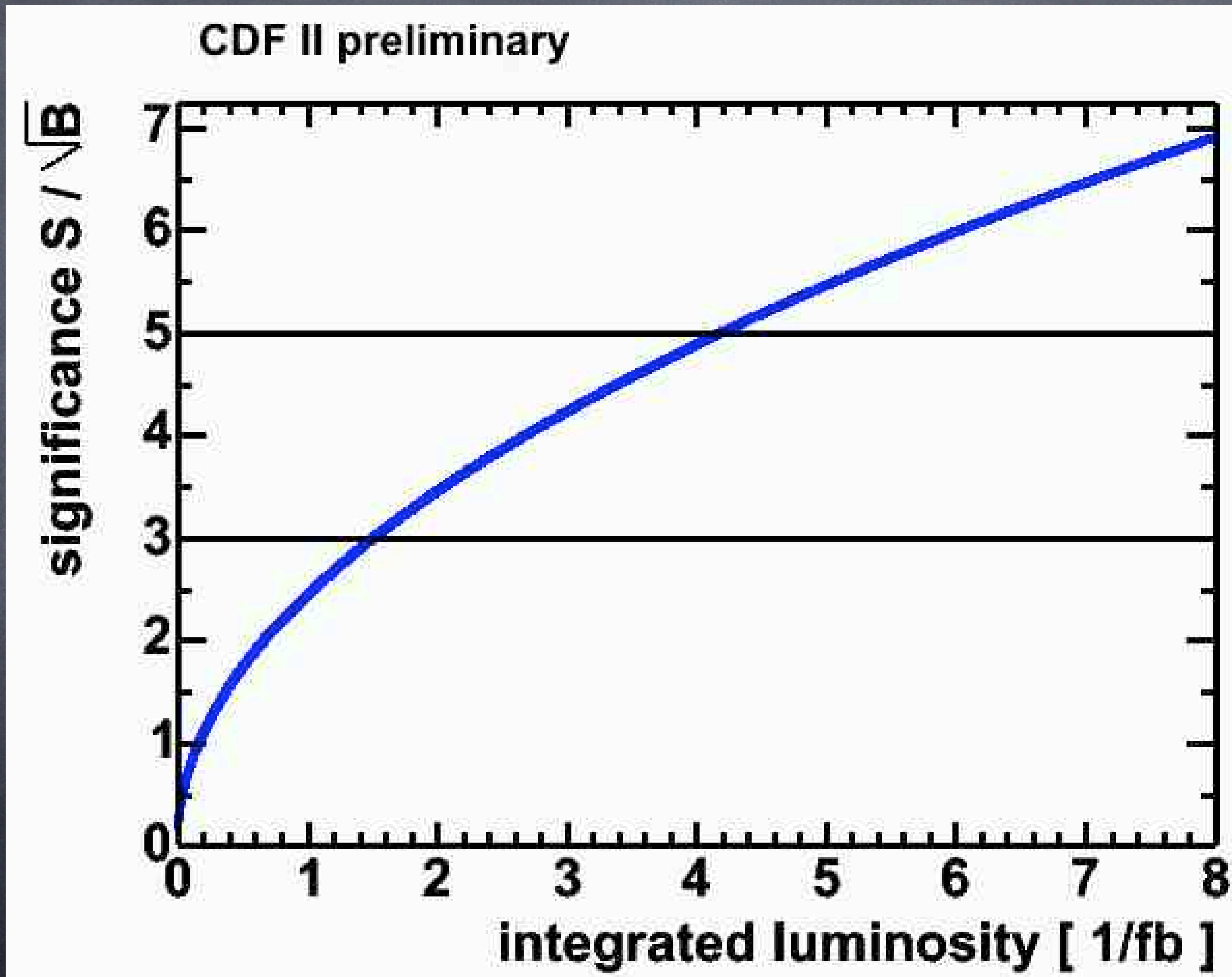
- The cross sections are known at NLO, including differential distributions.
- They are available in popular codes such as MCFM and ZTOP.
- There are also parameterized NLO effects in some LO codes (based on compHEP for example).

root S = 2 TeV



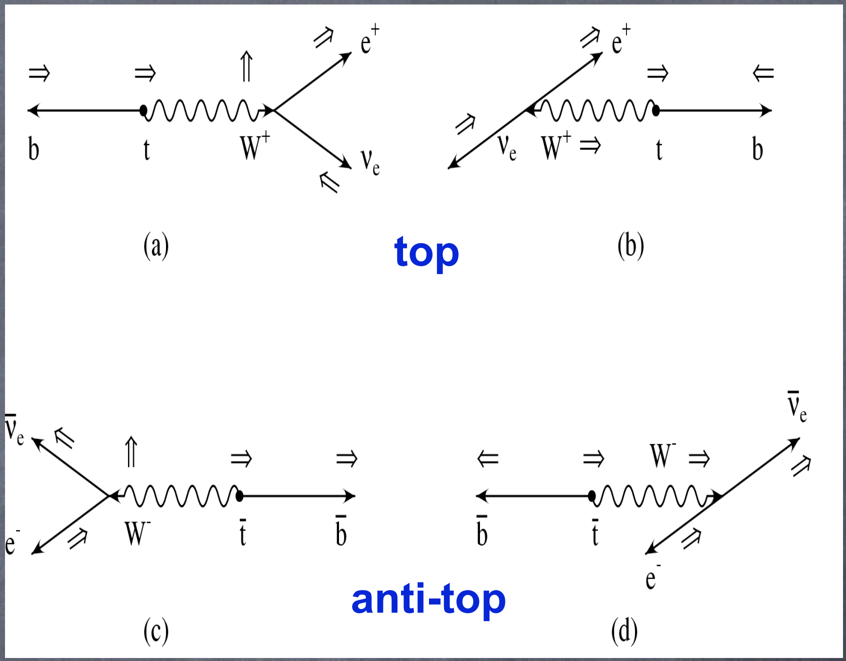
top + anti-top summed

We're getting close!



Polarization

- The fact that single tops are produced in the SM through the weak interaction implies that they tend to be polarized (because the weak interaction is left-handed).
- The polarization of the top can be reconstructed along some axis by looking at the decay products (again, the weak interaction).
- The existing analyses which measure t tbar are very useful; they calibrate the left-handed nature of the SM W-t-b interaction, and allows us to study the polarization from the production mechanism reliably.
- Because of the large top mass, the helicity basis is not optimized for polarization (though it works well). Optimal bases can be constructed for the SM dynamics.



The top (anti-top) spin tends to be in the same (opposite) direction as the charged lepton in the top rest frame.

Mahlon, Parke PLB476 323 (2000); PRD55 7249 (1997)

New Physics

- I'll show how the s- and t-channel modes can respond differently to new physics.
- This is partly based on the signatures and partly based on the underlying structure of SM single top production.
- In considering new physics effects, I divide into two classes:
  - New (charged) particles that couple to single tops.
  - Modifications of interactions which are already present (at some level) in the SM. These could be the effect of particles too heavy to be directly produced, or residuals of some new non-perturbative physics.

Charged Higgs

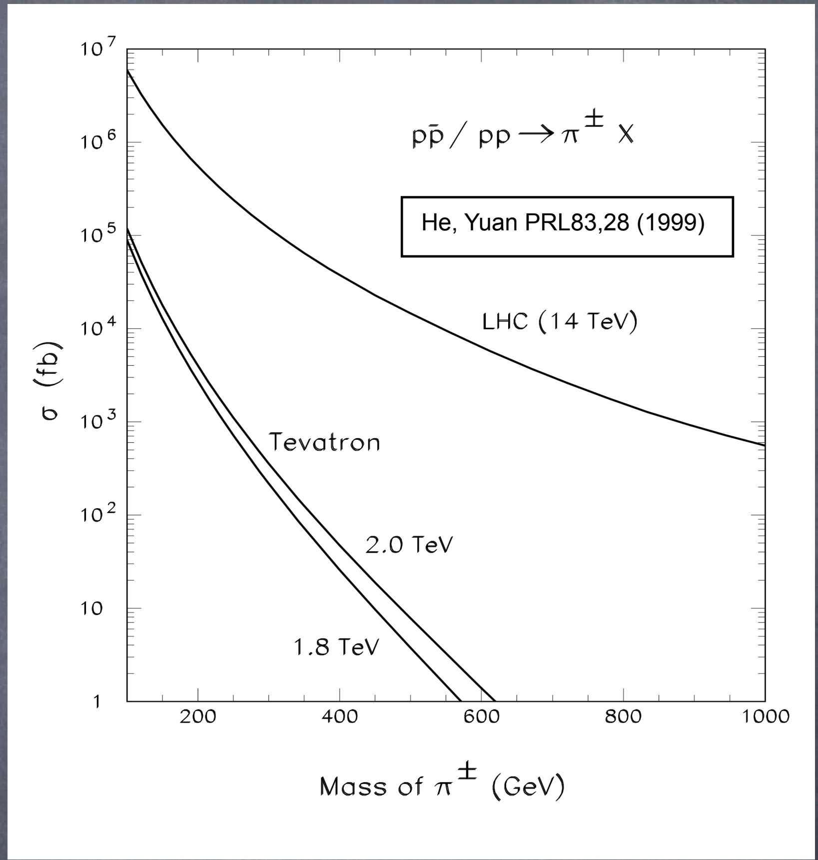
- Models with extended Higgs sectors often have charged scalars. Their interactions are often related to fermion masses and thus largest for top.

- One (famous) example is the minimal supersymmetric standard model.

- Top-color assisted technicolor has two electroweak symmetry breaking sectors, and thus also physical charged scalars.

- In the s-channel, we can produce the scalars (perhaps from a charm-bottom initial state). The large coupling to top allows a decay into t b, which fits the signature for s-channel single top production.

- In the t-channel, the cross section is suppressed by the large Higgs mass!



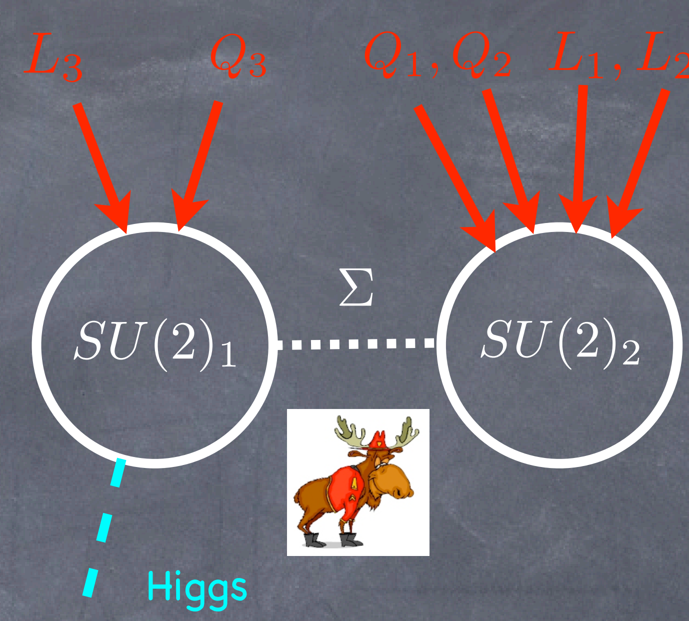
$$\mathcal{M} \propto \frac{g_{H^\pm}^2}{s - M_{H^\pm}^2 + i M_{H^\pm} \Gamma_{H^\pm}}$$

s > 0

$$\mathcal{M} \propto \frac{g_{H^\pm}^2}{t - M_{H^\pm}^2}$$

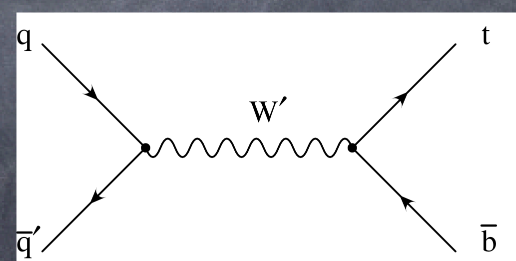
t < 0

W's



- Some theories have W's that prefer to couple to top (or the third family).
- Examples are found in some technicolor models, topflavor, and deconstructions of extra dimensions with weak interactions in the bulk!
- We can produce a W′ on-shell and then allow it to decay. If it couples more strongly to the third generation, the largest BR is likely to be t b! This contributes to the s-channel signature.
- The W′ can be exchanged in the t-channel, but this is suppressed by the heavy W′ mass (just as it was for the charged Higgs).

Chivukula, Simmons, Terning PRD53, 5258 (1996)
Muller, Nandi PLB383, 345 (1996)
Malkawi, Tait, Yuan PLB385, 304 (1996)



New Interactions

- A model independent way to study new physics is provided by effective Lagrangians, adding interactions beyond those in the SM.
- The SM already contains all renormalizable interactions (with couplings of mass dimension 4 or less); we must include non-renormalizable terms.
- Couplings for 'higher dimensional' operators have negative dimension so that the Lagrangian stays at dimension 4:

Counting Dimension

Ψ	: 3/2
H, V_μ	: 1
∂_μ	: 1

$$\overbrace{g}^{\text{dimension } 0} \times \overbrace{\underbrace{\overline{\Psi}}_{3/2}\gamma_\mu \underbrace{\Psi}_{3/2}\underbrace{V^\mu}_{1}}^{\text{dimension } 4} \qquad \overbrace{\frac{1}{\Lambda^2}}^{\text{dimension } -2} \times \overbrace{\underbrace{\overline{\Psi}}_{3/2}\gamma_\mu \underbrace{\Psi}_{3/2}\underbrace{\overline{\Psi}}_{3/2}\gamma^\mu \underbrace{\Psi}_{3/2}}^{\text{dimension } 6}$$

- This theory makes sense as an expansion in energy. Observables depend on **E^n / Λ^n**, so provided **$E \ll \Lambda$**, the expansion makes sense.
- Gauge symmetries of the Standard Model such as SU(3) invariance, etc. are still respected by the new interactions.
- They can be understood as residual effects from very heavy particles.

Non-standard Top Interactions

- Top may couple in a funny way to strange, down, or bottom:

$$\frac{g}{\sqrt{2}}\sum_i \left(\kappa_R^{Wtd_i}\bar{t}\gamma_\mu P_R d_i + \kappa_L^{Wtd_i}\bar{t}\gamma_\mu P_L d_i\right)W_+^\mu + h.c.$$

  - All of these modify all single top rates.
  - But aren't these operators dimension 4?
    - Yes, but their SU(2)xU(1) description was dimension 6!

$$\frac{1}{\Lambda_{Wts}^2}\left(H^\dagger H\right)\overline{Q_3}\gamma^\mu\left(D_\mu Q_2\right) + h.c.$$

$$\rightarrow \frac{\left(v^2\right)}{\Lambda_{Wts}^2}\bar{t}\gamma^\mu P_L\left(W_\mu^+ s\right) + \ldots$$

- Top may have FCNC's with up or charm and Z/g/γ:

$$\frac{g}{\cos\theta_W}\sum_i \left(\kappa_R^{Ztu_i}\bar{t}\gamma_\mu P_R u_i + \kappa_L^{Ztu_i}\bar{t}\gamma_\mu P_L u_i\right)Z^\mu + h.c.$$

$$+ g_S\sum_i \left(\frac{1}{\Lambda_R^{gtu_i}}\bar{t}\sigma_{\mu\nu}P_R u_i + \frac{1}{\Lambda_L^{gtu_i}}\bar{t}\sigma_{\mu\nu}P_L u_i\right)G^{\mu\nu} + h.c.$$

$$+ \frac{2}{3}e\sum_i \left(\frac{1}{\Lambda_R^{\gamma tu_i}}\bar{t}\sigma_{\mu\nu}P_R u_i + \frac{1}{\Lambda_L^{\gamma tu_i}}\bar{t}\sigma_{\mu\nu}P_L u_i\right)F^{\mu\nu} + h.c$$

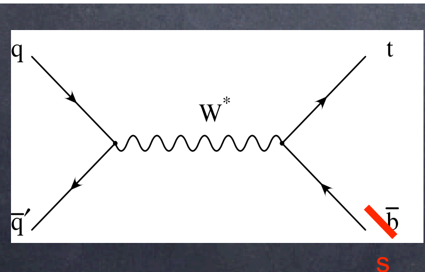
These processes also lead to FCNC top decays!

New Charged Interactions

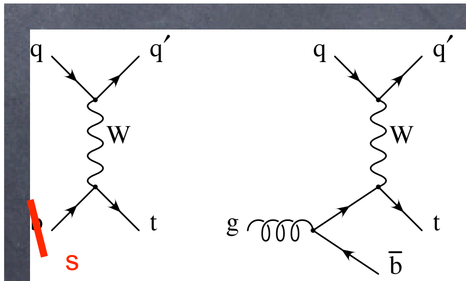
- As a first case, let's turn on a W-t-s interaction.
- To make things interesting, I will dial down the W-t-b interaction at the same time.

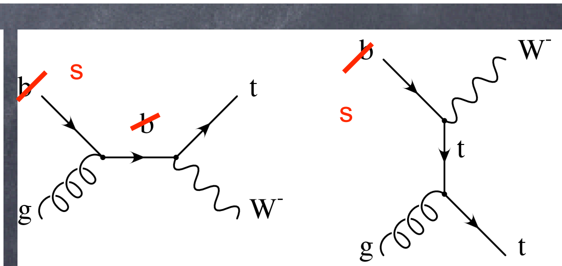
$$\begin{bmatrix} 0.9745 & 0.224 & 0.0037 \\ 0.224 & 0.9737 & 0.042 \\ \color{magenta}{0.008} & \color{blue}{0.040} & \color{red}{0.9991} \end{bmatrix}_{SM} \Rightarrow \begin{bmatrix} 0.9745 & 0.224 & 0.0037 \\ 0.224 & 0.9737 & 0.042 \\ \color{magenta}{0.008} & \color{blue}{0.55} & \color{red}{0.835} \end{bmatrix}_{Effective}$$

- All three single top modes change:



s-channel: over-all rate unchanged, but now we produce t s 1/3 of the time.





t-channel and **tW**: The rates themselves change, because now there is significant production from an initial state strange quark, with a larger probability than bottom to be found at high ***x*** in the proton.

FCNC's

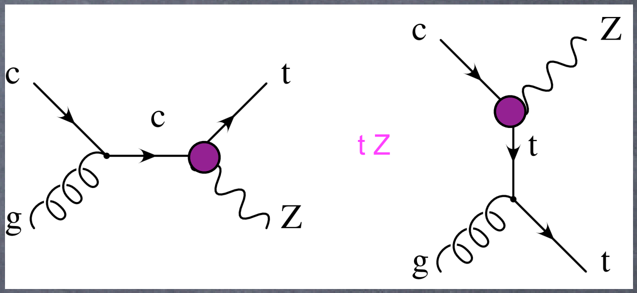
- As a 2nd example, consider a FCNC interaction of Z-t-c:

$$\frac{g}{\cos\theta_W}\left(\kappa_R^{Ztc}\bar{t}\gamma_\mu P_R c + \kappa_L^{Ztc}\bar{t}\gamma_\mu P_L c\right)Z^\mu + h.c.$$

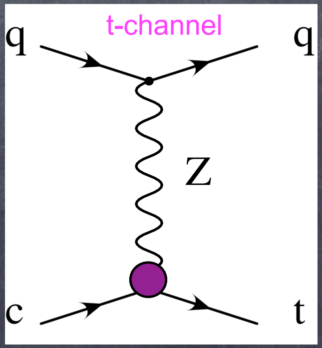
Note left- and right-handed versions – influence polarization!

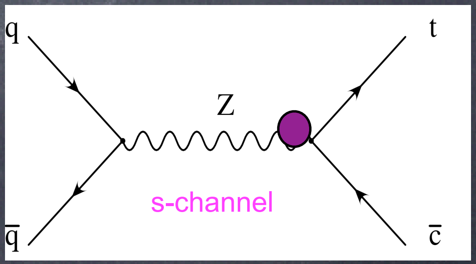
(I could have chosen Z-t-u instead or as well)

- These do not modify the SM s-channel or Wt rates. Instead, they introduce new processes. (The new s-channel process doesn't get counted as such because it has no final state b to tag).



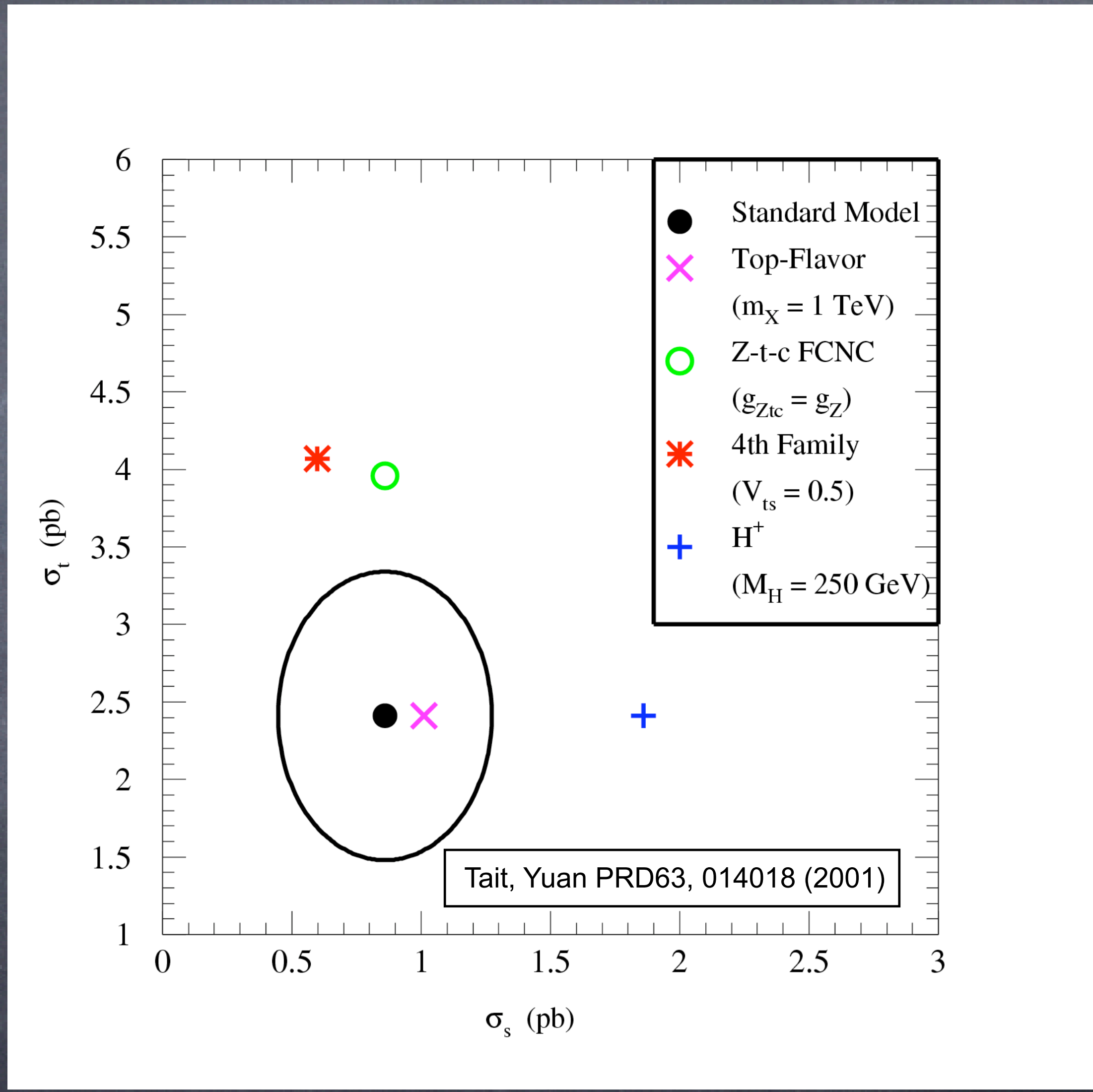
- The t-channel rate is enchanced by a charm-initiated process! As in the W-t-s story, this takes advantage of more c than b in the proton...



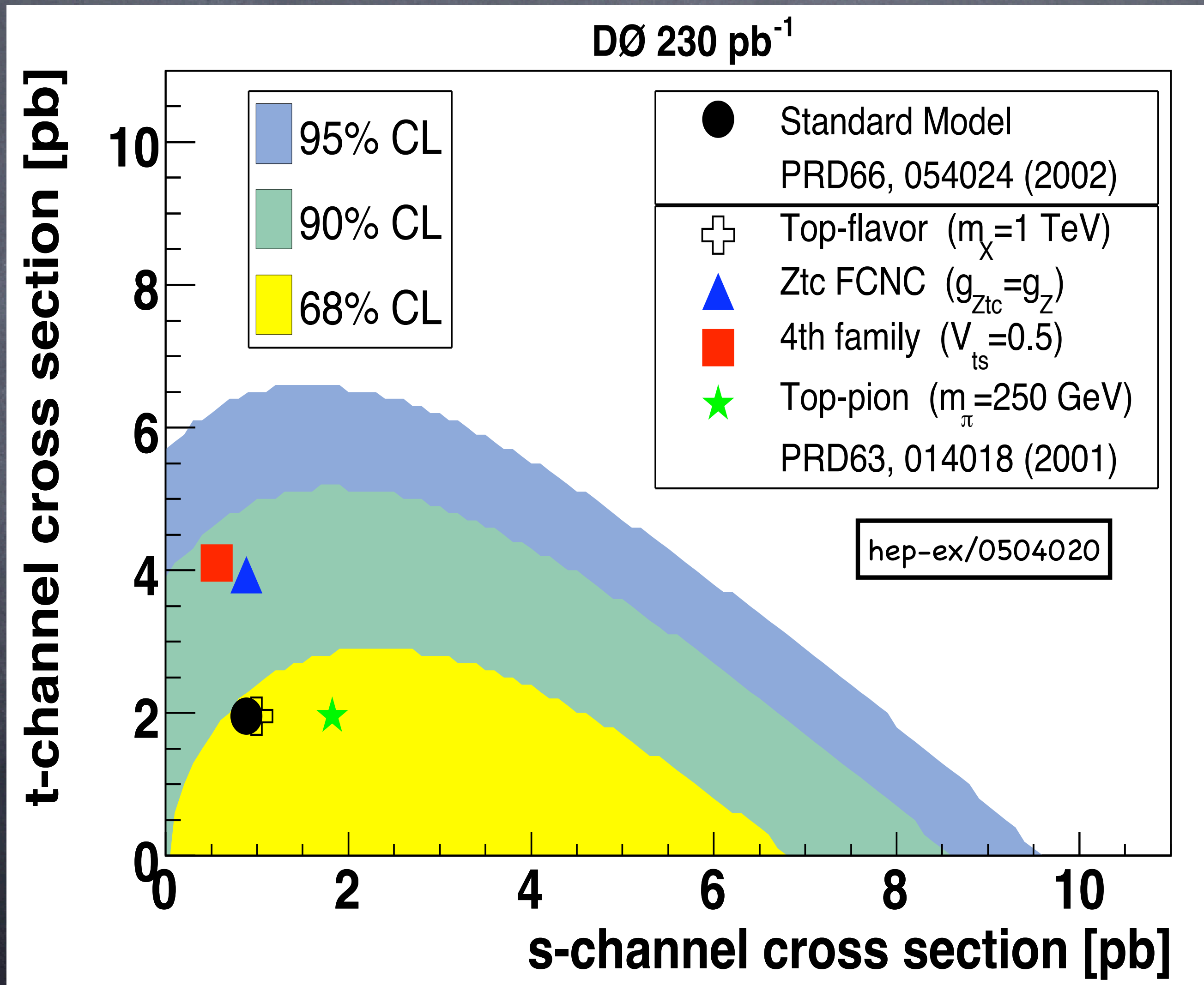


Information from Rates!

- All together, this shows how the different modes have different sensitivities to different forms of new physics.
- Since they have different characteristics, they can be measured independently.
- The correlation of the two could help us identify new physics if there is a deviation!



...and it already constrains some models!



Outlook

- We're on the verge of seeing single top for the first time! This will be our first direct glimpse of the top's weak interactions.
- Single top production is sensitive to many specific types of physics beyond the SM. But more generally if we think the large top mass is the result of a special connection between top and EWSB, the weak interactions of top are **exactly** the place to look!
- The rates of the s- and t-channel modes are sensitive to different types of new physics.
- Once we have events, the SM predicts strong polarization which we can test looking at top decay products!